PB86-144607

Vertical Transport by Cumulus Clouds

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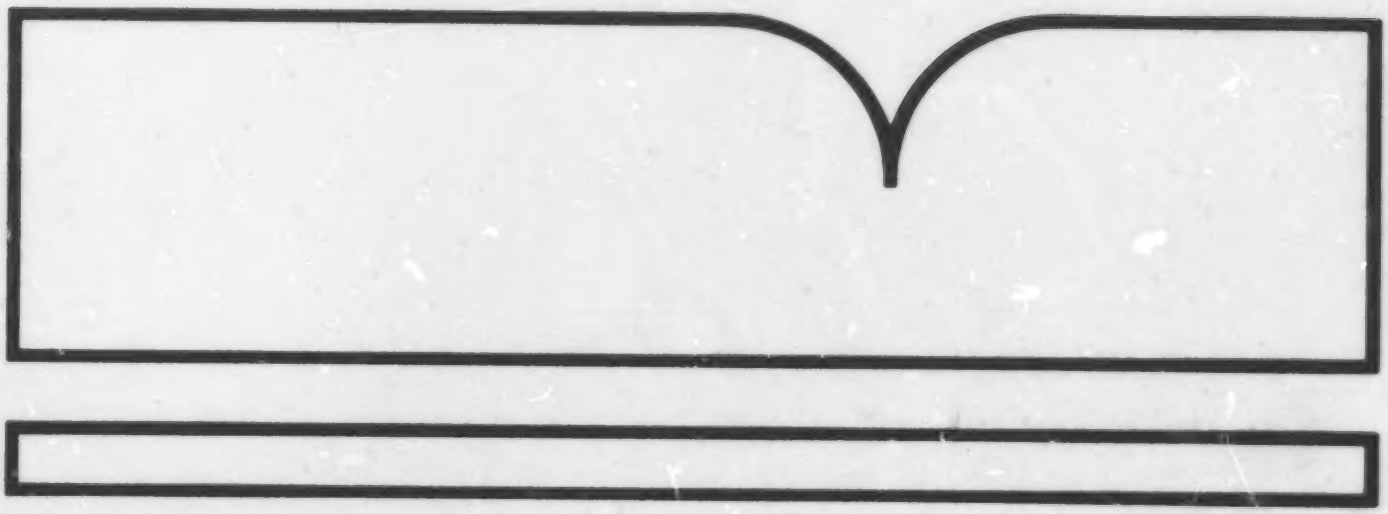

U.S. Department of Commerce
National Technical Information Service
NTIS

PB86-144607

EPA/600/D-86/001
December 1985

VERTICAL TRANSPORT BY CUMULUS CLOUDS

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IAG DW89930059

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TECHNICAL REPORT DATA
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1. REPORT NO. EPA/600/D-86/001	2.
3. RECIPIENT'S ACCESSION NO. PB86 144607/AS	
4. TITLE AND SUBTITLE VERTICAL TRANSPORT BY CUMULUS CLOUDS	5. REPORT DATE December 1985 6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) Ching, J.K.S., and A.J. Alkezweeny	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Pacific Northwest Laboratory Richland, Washington, 99352	10. PROGRAM ELEMENT NO. CCVN1A/01-3095 (FY-86) 11. CONTRACT/GRANT NO. (IAG) DW930059
12. SPONSORING AGENCY NAME AND ADDRESS Atmospheric Science Research Laboratory-RTP,NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, NC 27711	13. TYPE OF REPORT AND PERIOD COVERED 14. SPONSORING AGENCY CODE EPA/600/09
15. SUPPLEMENTARY NOTES	

16. ABSTRACT

The exchange process between the mixed layer and the free troposphere by non precipitating cumulus convective clouds is examined based on results of two field experiments conducted in Lexington, Kentucky. The first experiment utilized SF_6 tracer gas released from one aircraft and sampled by another at various levels in and above the mixed layer as well as on the ground. In one scenerio, the tracer was released below the active cloud base, was subsequently observed at and above cloud tops, indicating that pollutants from the mixed layer penetrate the free troposphere by cumulus convection. In another scenerio, the tracer was released near cloud top (3 km above the surface) and high concentrations of the tracer was observed both within the mixed layer as well as at the ground. This result suggests that the cloud convective activity force cloud layer air back into the mixed layer and into its surface layer. Thus, the layer of turbulent mixing is deeper and more vigorous in the presence of convective clouds, and the turbulence variance statistics near the surface are apt to contain large, but episodic variability localized within the domain of cloudiness. In the second experiment, pollutant accumulation over time above the mixed layer is in evidence from aircraft data along horizontal transects made in the cloud layer during periods of active cumulus activity for conditions when pollutant concentration in the mixed layer exceeded that in the layer above. This observation is shown to be a consequence of and a requirement for a net upward flux of pollutants at the top of the mixed layer.

17. KEY WORDS AND DOCUMENT ANALYSIS		
a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group

18. DISTRIBUTION STATEMENT RELEASE TO PUBLIC	19. SECURITY CLASS *(This Report)* UNCLASSIFIED 20. SECURITY CLASS *(This page)* UNCLASSIFIED	21. NO. AGES 22. PRICE

EPA Form 2220-1 (Rev. 4-77) PREVIOUS EDITION IS OBSOLETE

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VERTICAL TRANSPORT BY CUMULUS CLOUDS

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1. INTRODUCTION

Pollutants from the mixed layer are expected to be exchanged with air from the overlying free troposphere by cumulus convective activity. The importance of this process in determining regional scale air quality or acid deposition is currently being evaluated. Recent field measurements (Ching et al. 1984) have indicated that cumulus clouds carry mixed layer pollutants into the free troposphere. That study utilized the NASA airborne UV DIAL system that can by remote means monitor the vertical profiles of ozone and aerosol backscatter below the aircraft. The air mass that contained penetrative cumulus clouds during the afternoon was sampled in the early evening, long after the cloud activity had concluded, and the clouds had evaporated. The data showed complex distribution and structure of polluted layers which were inferred to arise from the dissipated clouds. These layers were tilted in the vertical as expected if a vertical cloud column were subjected to wind shear as was present on the sampling day; additionally, the ozone and the aerosol distribution were highly correlated within these layers. In other studies that utilized fast response ozone sensors and gust probe systems on aircraft, fluxes of ozone were measured across a field of convective cloud elements (Ching et al.1983, Stull and Eloranta,1984) and for clouds over an urban area (Greenhut et al. 1984). Isaacs et al.(1983) also argue that convective clouds vertically transport pollutants out of the subcloud layer. They define a vertical transport ratio, VTR, as the volume of subcloud air pumped through the cloud base relative to the total volume of the subcloud layer. Their preliminary analyses suggest extreme VTR values of 50%/hr in summer and 20%/hr during other seasons. Liu et al. (1984) analyzed 38 vertical profile measurements of Radon 222, an inert gas of continental ground origin. They concluded that 55% of the Radon 222 was transported out of the mixed layer during the summer months while much smaller transport occurred during other seasons. Gidel (1983) modeled the vertical transport of transient tracers by cumulus clouds using a one-dimensional steady-state entrainment model and cloud population statistics imposed as an ensemble distribution of clouds of various heights. He found that pollutant mixing ratios will increase above a background that was not influenced earlier by cloud transport. Measurements by Chatsfield and Crutzen, (1984) qualitatively substantiate Gidel's results. Liu et al.(1984) finds their Radon 222 profiles to fall between Gidel's cloud and no-cloud model results when applied to their data.

2. VENTEX FIELD STUDY

This paper provides results of a summer 1983 experimental field program called VENTEX (VENTing EXperiment) which took place in the vicinity of Lexington, KY. This study was sponsored by the US Environmental Protection Agency and conducted by Pacific Northwest Laboratory as part of the National Acid Precipitation and Assessment Program. During the study, a tracer gas was released and sampled to study the exchange processes between the mixed layer and the free troposphere resulting from non precipitating convective cloud activity. Additionally, air quality data were obtained by aircraft to determine if an accumulation of pollutants arises at the top of the mixed layer due to the induced flux convergence generated by the cumulus clouds.

2.1 Upward Vertical Transport

To study the vertical transport by cumulus clouds we used a nonreactive tracer, sulfur hexafluoride (SF_6) gas, to track air parcel trajectories into and out of the clouds. This tracer

+ On assignment from the National Oceanic and Atmospheric Administration, US Department of Commerce.

was chosen because it is nontoxic, easy to measure in parts-per-trillion concentrations, and relatively inexpensive to use. The tracer was released in the mixed layer at the rate of 28 l/min for approximately 1 hour by one aircraft repeatedly flying over the same 16 km crosswind path to simulate an area source, while a second aircraft performed the sampling. During the SF_6 release, the sampling aircraft was stationed several miles downwind of and at a different altitude from the release aircraft. The samples were collected in tedlar bags for later analyses. Since it took approximately 30 seconds to fill each bag with ambient air, the measured concentration is an average over a distance of about 2 km for the aircraft speed of 64 m/s. The analyser was a commercial gas chromatographic instrument that used an electron capture detector.

The experiment carried out on July 27, 1983 was designed to verify the hypothesis that clouds do transport mixed layer air into the cloud layer. During this day, fair weather cumulus clouds started to form at approximately 1100. (All times given are in Eastern Daylight Time.) By the time of the tracer release at 1512, the clouds covered about 50% of the visible sky. The wind at the ground and aloft was light throughout the day. The mixed layer height determined from the aircraft sounding was 1900m (all altitudes are given above ground unless otherwise indicated). The SF_6 tracer was released for a period of 1 hour, about 70 km northeast of Lexington, KY at an elevation of 1400m along a line 16 km long, and oriented across the prevailing wind direction at this altitude. Cloud bases were located at 1750m, and their tops were at about 2000m. The sampling aircraft flew at a constant altitude of 2200m and bag samples were collected between 1524 and 1543. Sampling was also conducted between 1550 and 1630 at an elevation of 2500m. Figure 1 shows the release line and the sampling aircraft flight route. (The tracer concentrations are shown superimposed on the flight route.)

The results provide evidence that convective clouds transport air out of the mixed layer. The

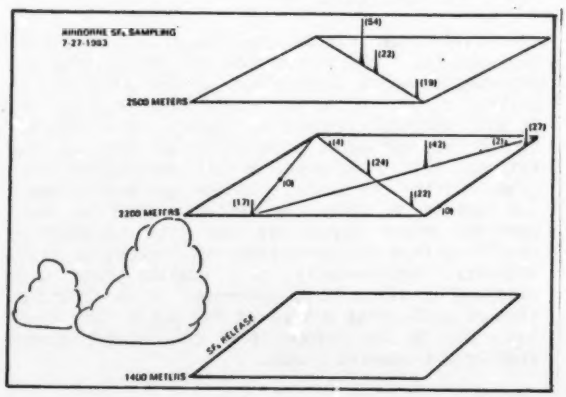

Figure 1. Sulfur Hexafluoride (SF_6) below-cloud release and sampling routes on July 27, 1983. Numbers in parentheses are concentrations in parts-per-trillion of SF_6 gas. Heights in meters above ground level are indicated; the plane of the tracer and the aircraft sampling is horizontal.

SF_6 measurements exhibited large variations between samples and the concentrations were much larger than can be supported by typical diffusive mixing conditions. This can be demonstrated by an order of magnitude analysis. For an SF_6 emission rate of 28 l/min at constant elevation along a crosswind path of 16 km repeated over a one hour period and with a 5 m/sec advecting wind, these emissions would cover an area of approximately 300 km^2. For analysis purposes only, if uniform mixing is assumed through a depth between the surface and the cloud tops, at 2.5 km, corresponding to a volume of order 10^3 km^3, the resulting SF_6 mean values will be of order 1 to 5 ppt. However, the observed concentrations at cloud tops and at levels above cloud tops were significantly larger, varying between 10 and 300 ppt. These measurements suggest that the diffusion process is relatively less important than cloud updrafts for the transport from the mixed layer, and the large variations observed suggests the process to be highly episodic in nature. Additionally, since large concentrations of the tracer were measured at levels above the visible cloud tops there is the strong suggestion that these clouds induce transport beyond the visible extent of the clouds.

2.2 Downward Vertical Transport

The second type of experiment, conducted on August 16, 1983, was designed to examine the transport from the cloud layer to the mixed layer. Cumulus clouds began to form about 1130 and by the afternoon the cloud cover was estimated at about 70%. Cloud bases were at approximately 1300m, and their tops were generally at 2500m; some towers extended to 2800m. The mixed layer height was 2000m. The wind at the ground and aloft was light. SF_6 was released above cloud tops, between 2500 to 2670m, along a 16 km line that was oriented across the wind. The release time was between 1400 and 1500. Sampling was done both aloft and on the ground downwind of the Lexington airport release site. The emissions flight and the results of the aircraft sampling are shown in Figure 2. Note that the first airborne sample was taken at about 3200m, more than

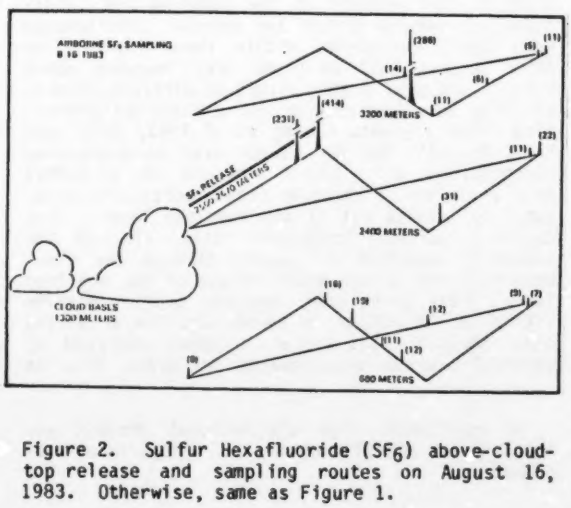

Figure 2. Sulfur Hexafluoride (SF_6) above-cloud-top release and sampling routes on August 16, 1983. Otherwise, same as Figure 1.

500m above the tracer release altitude, and about 15 minutes after the release was stopped (from 1514 to 1530). The aircraft then descended to 2400m within the cloud layer and sampled from 1554 to 1638. The final sample collection was made within the boundary layer at 680m above the ground, but 620m below cloud bases near the release area. Once again, the tracer was found in high concentrations and exhibited large spatial variations at an altitude considerably higher than the tops of the visible cloud tops, consistent with the other study.

However, the remarkable aspect of this experiment was the clear evidence of tracer entering into the mixed layer and even arriving at the surface in large and highly intermittent concentrations. Results of the ground measurements are shown in Figure 3. These observations suggest that the downdraft velocities for a significant fraction of the compensating area must be large and in close proximity to the updraft region of individual cloud elements. The reasoning behind this hypothesis is as follows: If the mass required to balance the cloud updraft takes place as an augmentation of the general synoptic-scale subsidence, say of order 1 cm/sec, and the detrainment took place in the upper levels of the cloud or even at cloud tops, the tracer would arrive at the top of the mixed layer at least 6 to 12 hours after the time of cloud activity. At that time, the ability to entrain this material into the mixed layer would be limited since the turbulent intensity at this time of the diurnal cycle is markedly reduced. The observations, however, indicate that the SF_6 was greatly in excess of the 1 to 5 ppt values that would have been observed if the tracer were uniformly distributed within the mixed layer since the observed values were one order of magnitude larger. Furthermore, the time at which the tracer was observed at the surface was only 1/2 hour after the initiation of the tracer release. This requires a minimum downdraft speed of 1.4 m/sec to explain this observation. Additionally, the surface measurements showed the SF_6 concentration to be highly intermittent with values varying between 5 and 30 ppt. The concept of downdrafts strong enough to reach the surface (or at least to the top of the mixed layer where mixed layer processes can further transport the tracer to the surface) which are induced by the convective updrafts of the cumulus clouds, provides a highly plausible and consistent explanation to this set of conditions.

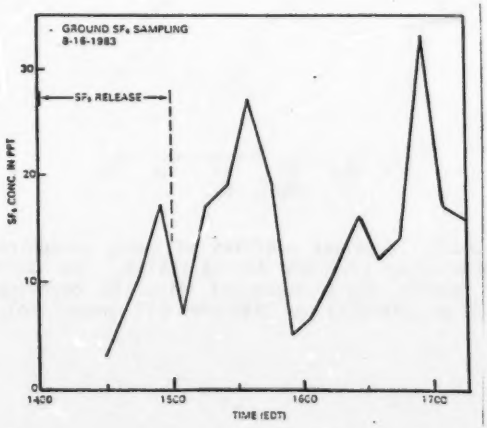

Figure 3. Concentrations of SF_6 measured at the surface and downwind of the release line for August 16, 1983.

Finally, if the tracer that was released in the free troposphere fumigates into the mixed layer as a result of these downdrafts, and if it's deposition to the surface is small, the SF_6 concentration in the mixed layer should increase as a consequence of a negative vertical flux divergence. There appears to be some indication of a positive trend in the surface measurement of the SF_6 tracer.

2.3 Accumulation Mode

A net flux of pollutants above the cloud base will increase the pollutant loading in this layer. In 1984, another VENTEX study was conducted in Lexington, KY. As part of that study, a Cessna 411 aircraft collected air quality and meteorological data to study vertical transport by clouds. Results of the aircraft penetrations through cloud tops at constant altitude on July 13, 1984 are shown in Figure 4. An individual cloud is identified by the rise in the ozone, bscat and relative humidity data. The in-cloud and environment concentration difference of ozone is in the range of 5 to 15 ppb. The vertical profiles of ozone from aircraft soundings outside of Lexington are shown in Figure 5 for a morning and afternoon sounding. At 1130 the top of the boundary layer, defined as the base of the elevated inversion was at about 2000m MSL. By 1645 the top had risen to 2200m MSL. Within the boundary layer the ozone concentration increased at all altitudes by approximately 20 ppb over the 5-hour period. Above the top of the mixed layer at 2200m MSL but below 2700m MSL, the top of the cloud layer, ozone concentrations are observed to increase providing evidence for accumulation in this layer by venting clouds. Above 2700m MSL the ozone concentration was pratically unchanged during this period. Clearly, vertical transport was occuring but was limited to the cloud layer and not above.

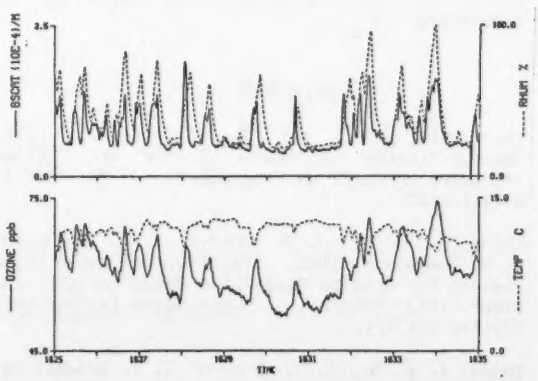

Figure 4. Cross sectional data of ozone, temperature, bscat and relative humidity derived from an aircraft cloud top penetration flight on July 13, 1984.

3. DISCUSSION

There is much to be learned regarding the nature of the up and downdrafts associated with these cloud motions. The areal extent and distribution of the downdraft relative to the updraft region might be quite limited, in which case the magnitude of the downdraft could be comparable to that of the updrafts. In this situation, these downdrafts may be very effective in mixing cloud layer air towards the surface. If on the other extreme, the mass redistribution should occur over a much larger area, the resulting subsidence velocity will be relatively small and consequently, the mixing will be limited to the interfacial or entrainment layer. This study supports the former scenerio.

Recent observational studies favor the return pathway to be near or adjacent to the updraft region and of comparable magnitude to the updraft speeds. Kitchen and Caughey (1981) using a tethered balloon observed a "P" shaped distribution. They suggest a mechanism called CIFKU (Convective Instability of the First Kind Upside down) proposed by Randall (1980) to be consistent with their observations. Uthe et al. (1985) studied clouds of nontoxic fluorescent dye particles released both below and above cumulus clouds and monitored the transport and dispersion of these tracers using an airborne lidar. They observed that the dye released below clouds was vented upward into the clouds; the dye released at and above the tops of the cloud rapidly descended into the mixed layer.

The following picture emerges: pollutants are carried upward to the cloud layer by thermal plumes or cloud updrafts. The cloud layer consists of fair weather cumulus clouds, and towering clouds in various stages of their growth. The towering clouds penetrate deep into the free atmosphere and when they evaporate they leave the transported material behind. The detrainment occurs primarily at and above the cloud top. On the other hand, the downdrafts associated with these clouds bring free tropospheric air into the mixed layer and ultimately to the ground. The implication of this result is that in the presence of cumulus convective cloud activity the layer of turbulent mixing is deeper, more vigorous, and apt to be localized within the domain of the cloudiness.

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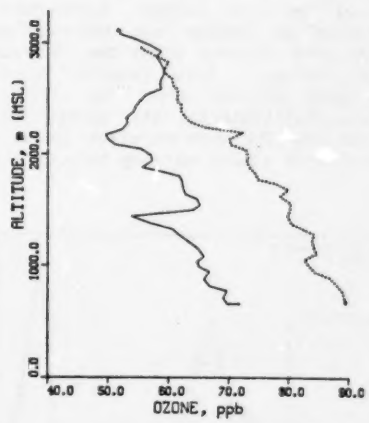

Figure 5. Vertical profiles of ozone concentration of July 13, 1984 during VENTEX. The solid and dotted lines represent aircraft soundings taken at 1126-1143 and 1645-1700 EDT respectively.

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